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Forsmark site investigation

Bio- and lithostratigraphy in offshore sediment core PFM004396

Salinity variations in the Bothnian Sea offshore Forsmark

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December 2005

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Keywords: Sediment, Quaternary deposits, Marine geology, Diatoms, Organic carbon, Salinity, Yoldia Sea, Littorina Sea, Sedimentation, AP PF 400-04-116.

Abstract

This work deals with stratigraphic analyses of a six metre long sediment core called PFM004396 collected offshore Forsmark. The overall purpose is to interpret the results in terms of environmental changes. The sediment analysed consists of clay and clay gyttja.

The main part of the work comprises of stratigraphic analyses of siliceous microfossils, i.e. diatoms, Chrysophyte stomatocysts, sponge spiculae, ebridians, silicoflagellates, and phytoliths. Calcareous fossils were planned to be investigated but were not encountered. AMS radiocarbon dating of bulk sediment was applied to establish the age of the sediment sequence. Determinations of organic carbon content, grain size distributions and carbonate contents were used to describe the sediment composition.

The sequence was divided into nine zones and the following conclusions were drawn:

- Salinity during the Yoldia Sea stage was low since no finds of calcareous fossils were made. The highest salinity, c 15‰, prevailed between 7,000 and 4,500 cal yrs BP, i.e. during the Littorina Sea stage.
- Zone 1 represents sedimentation in the Yoldia Sea with an unknown accumulation rate. Zones 2–9 represent sedimentation in the Littorina Sea with continuous accumulation between 7,000 and 2,000 cal yrs BP.
- Sediment was either not accumulated during the Ancylus Lake stage and the beginning of the Littorina Sea stage (c 10,500–7,000 cal yrs BP) or eroded later. A second erosive phase is prevailing from c 2,000 cal yrs BP until present.
- The average accumulation rate during the Littorina Sea stage was c 0.9 mm/year.
- The accumulation rate of organic carbon varies between 15 and 35 mg C/year. There are increasing trends from zone 2 until zone 5, where a general decrease starts. In time this corresponds to c 4,500 cal yrs BP.
- The sediment is characterised by a high degree of clay particles. It is only in the uppermost c 50 cm that sand particles dominate. Carbonate contents are low except in the lowermost samples where 5 and 11% were measured.

Sammanfattning

Arbetet omfattar bio-, lito- och kronostratigrafiska analyser av en sex meter lång sedimentkärna benämnd PFM004396, insamlad utanför Forsmark. Det övergripande syftet var att applicera ett antal anlysmetoder vilkas resultat tolkades med avseende på miljöförändringar, speciellt salinitet. Det analyserade materialet bestod av lera och lergyttja.

Analysmetoderna omfattade kiselmikrofossil (speciellt diatoméer), kalkskaliga fossil, organiskt kol, kornstorleksvariationer och karbonathalter. För att få en uppfattning om åldern på olika delar av sedimentkärnan daterades bulksediment med AMS-metoden (C^{14}).

Baserat på stratigrafiska variationer av kiselmikrofossil delades sekvensen in i nio zoner med följande slutsatser:

- Saliniteten under Yoldia-stadiet var låg. Den högsta saliniteten, ca 15 ‰, rådde mellan 7 000 och 4 500 kalibrerade år BP, dvs under Littorina statidet.
- Zon 1 representerar sedimentation i Yoldiahavet. Zonerna 2–9 representerar sedimentation i Littorinahavet med kontinuerlig ackumulation mellan 7 000 och 2 000 kalibrerade år BP.
- Mellan ca 10 500–7 000 kalibrerade år BP, dvs under Ancylusstadiet och början av Littorinastadiet, avsattes inga sediment på provtagningsplatsen, alternativt eroderades i ett senare skede. En andra erosiv fas har rått under de senaste ca 2 000 åren.
- Medelackumulationshastigheten under Littorinastadiet var ca 0,9 mm/år.
- Ackumulationshastigheten av organiskt kol varierar mellan 15 och 35 mg C/år.
- Sedimenten karaktäriseras av en hög andel lerpartiklar. Det är endast i de översta ca 50 cm som sand blir dominerande. Karbonathalterna är låga förutom i de nedersta proverna som innehöll 5 respektive 11 %.

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1 Introduction

This document reports the results gained by the *Investigation of Marine geological sediment core offshore Forsmark*, which is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with Activity Plan AP PF 400-04-116. Controlling documents for performing this activity are listed in Table 1-1. Both Activity Plan and Method Descriptions are SKB's internal controlling documents. This work deals with stratigraphic analyses of the sediment core PFM004396 collected offshore Forsmark (Figure 1-1). The purpose is to interpret the results in terms of environmental changes. The work was performed during 2005. The original results are stored in the primary data bases (SICADA and/or GIS) and are traceable by the activity plan number.

Table 1-1. Controlling documents for performance of the activity.

Activity Plan	Number	Version
Investigation of Marine geological sediment core offshore Forsmark	AP PF 400-04-116	1.0

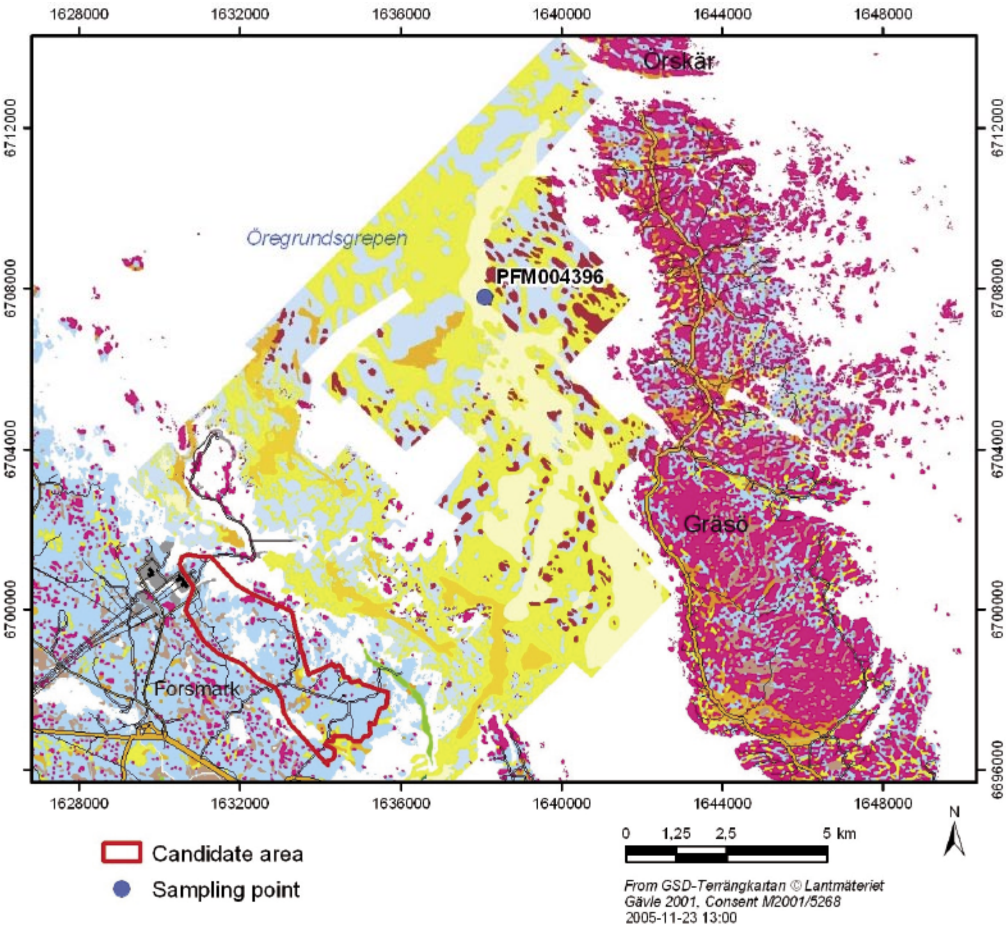

Figure 1-1. *Map showing the location for the sampling of the analysed sediment core PFM004396 and the map of Quaternary deposits on land and at sea bottom. Red is bedrock, blue is till, green is glaciofluvial sand and gravel, orange is postglacial sand and gravel, yellow is clay and brown is peat.*

2 Objective and scope

The Swedish Geological Survey conducted a detailed geologic mapping of the sea bottom offshore Forsmark during 2002 and 2003 following AP PF 400-02-27. The investigation consisted of hydro-acoustic mapping combined with sediment sampling. A six metre long sediment core, consisting of clay and clay gyttja, was collected at PFM004396 (preliminary labelled 13I-05). At the sampling occasion there was no plan of how to analyse the sediment and in what way the cores should be stored. This resulted in storage on the ship Ocean Surveyor during alternating relatively warm and freezing conditions. This treatment has probably resulted in a decreased sample quality, e.g. regarding the chemical properties. The sequence is, however, unique for the area, which normally is dominated by thin postglacial sedimentary layers. After visual inspection in November 2004 it was concluded that the core could reveal important information of relevance for the site description. The first inspection indicated that the core could represent a continuous record of the postglacial development of the Baltic basin. Therefore it was interpreted to represent an important archive for environmental changes during this time period.

The main part of the work consists of stratigraphic analyses of siliceous microfossils, i.e. diatoms, Chrysophyte stomatocysts, sponge spiculae, ebridians, silicoflagellates and phytoliths. Especially diatoms could indicate changes in salinity, water depth, nutrients and pH /Battarbee 1986, Lowe and Walker 1997/. Analyses of diatoms could therefore describe changes in the aquatic environment. Also eventual occurrences of calcareous fossils may be used to describe salinity changes.

AMS radiocarbon dating of bulk sediment was applied to establish the age of the sediment sequence. Determinations of organic carbon content, grain size distributions and carbonate contents were used to describe the sediment composition. The main purposes of this activity are as follows:

- to identify and quantify salinity variations during the various stages of the Baltic Sea since the latest deglaciation,
- to date the sediment core,
- to identify and date erosive phases, if any,
- to determine the sedimentation rate,
- to quantify the accumulation of organic carbon,
- to characterise the grain size composition and carbonate content.

In the interpretation of the sediment core, the following age intervals for the Baltic Sea stages are adopted: Baltic Ice Lake c 15,000–11,500, Yoldia Sea 11,550–10,800, Ancylus Lake 10,800–9,500, and Littorina Sea 9,500–0 cal yrs BP /Björck and Svensson 2002/.

3 Equipment

3.1 Sample treatment

The 6 m long core collected was split into two halves on the boat resulting in 12 one metre long plastic cylinders with a diameter of 60 mm (Figure 3-1). These were sealed with plastic surround rap and tightened in both ends. The sealing had in some cases been broken during storage on the boat. The lithostratigraphy of the Forsmark core was determined with respect to visible changes in sediment texture, grain size and inclusions. /Munsell soil color charts 2000/ were used to determine the colour of the sediment.

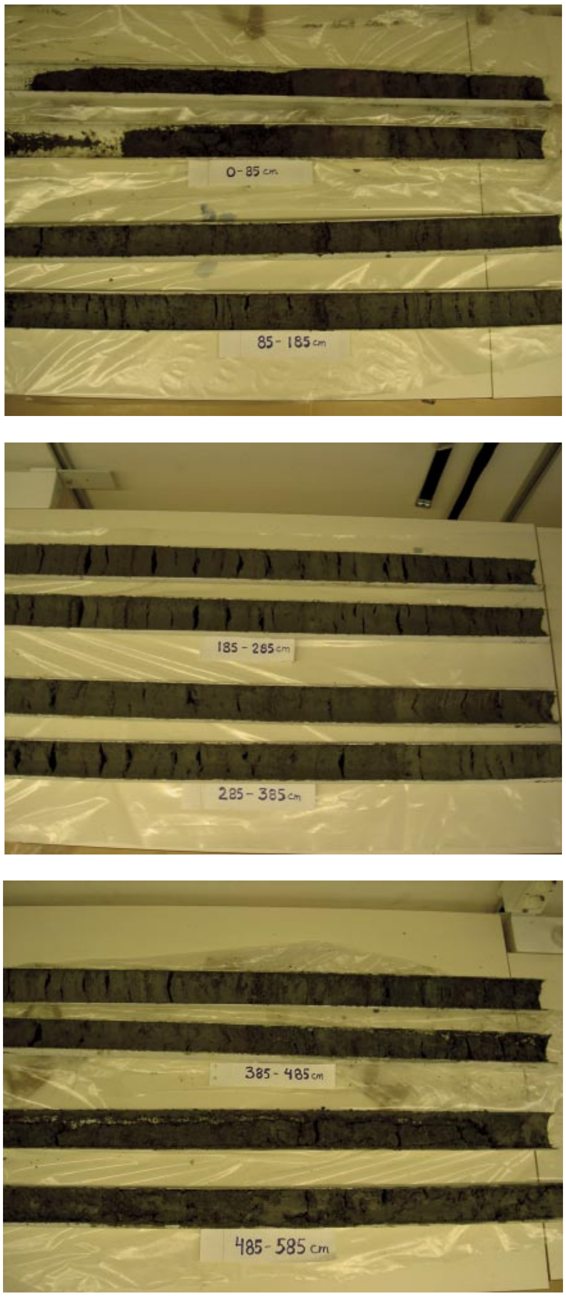

__Figure 3-1.__ Overview photographs of the cores analysed. Note that the upper 40 cm were not included in the sediment core.

3.2 Organic carbon

Samples for organic carbon analysis were collected at 5 cm intervals in order to estimate changes in biological productivity during the formation of Forsmark sediment record. Totally 110 sub-samples, with sample volumes of c 0.5–1.5 cm^3 were dried at 105°C, grounded and dried again (Figure 3-2). The large volume interval was caused by desiccation and subsequent cracking of the core. Samples (150–200 mg) were combusted at 500°C, thus oxidating the organic carbon to CO_2. The gas is analysed by infrared absorption in a Carbon Sulfur Determinator (Eltra CS 500) at the Department of Physical Geography and Quaternary Geology, Stockholm University.

Normally, the measuring time was 2–5 min. The samples between 580–500 cm depth required, however, up to 15 min measuring time.

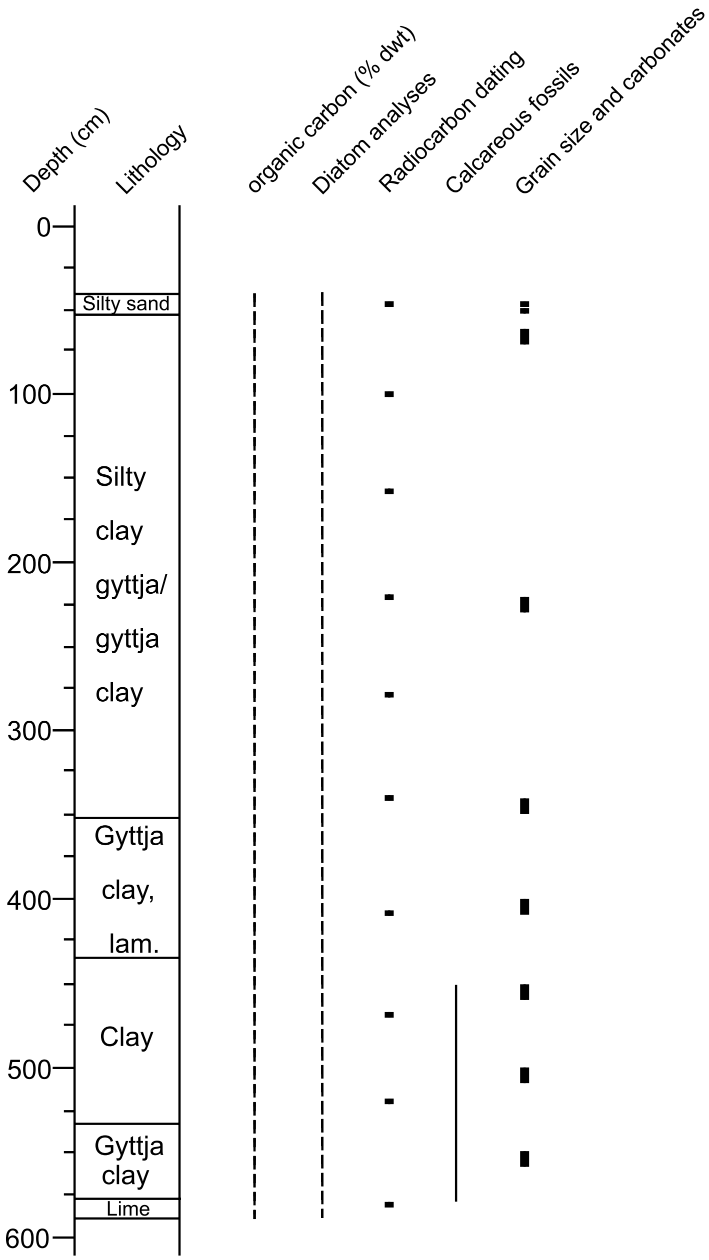

__Figure 3-2.__ Compilation of analyses, methods, sampling intervals and depths for each method applied to core PFM004396.

3.3 Diatom analysis

Variation in the sea water salinity during the sediment formation offshore Forsmark is based on diatom analyses, which were performed under microscope on samples enriched from one cm thick slices at 10 cm intervals (Figure 3-2). Totally 55 sub-samples (sample weight 0.5–2 g) were concentrated using standard procedures /Battarbee 1986/, and additional eight samples between 438–578 cm depth contributed to a quality control because of diatom poor samples within that sequence. 10% HCl was added to samples in order to remove e.g. carbonates before the oxidation of organic matter with hydrogen peroxide (17% and 30% H_2O_2). After boiling and washing with distilled water and weak nitric acid (5 ml HNO_3/litre distilled H_20), the prepared suspensions of diatoms were mounted on slides with Naphrax®. Proportions of diatom forms occurring were calculated as percentages of the total sum in the sample and grouped after their salinity preferences /Miller and Florin 1989/. The microscope used for identification of diatom frustules and other siliceous microfossils was a Leica DMLB with X1,000 magnification and immersion oil.

Extractions were repeated on several sub-samples (43, 83, 133, 143, 163, 173, 203, 213, 223, 243, 253, 263, 283, 303, 313, 323, 443, 453, 463, 473, 483, 493, 503, 523, 533, 543, 553, 563, 573 and 583 cm) because non-oxidizing sediment remains settled on the beaker bottoms. These were not soluble in hot 17% H_2O_2 but could either be of some unknown organic origin or the result from the repeated freezing/thawing process during storage.

Preparations were performed at the Department of Physical Geography and Quaternary Geology, Stockholm University.

3.4 Chronology

Ten AMS radiocarbon dates are based on 7–10 g bulk sediment. The samples are derived from one cm thick slices at 50 to 60 cm intervals (Figure 3-2). Only the organic fraction was dated and humic acids were removed by NaOH. This means that the insoluble (INS) fraction was dated. The samples were submitted to Poznan Radiocarbon Laboratory in Poland.

3.5 Calcareous fossils

The preparation technique used for extraction of calcareous fossils, i.e. foraminifera and Ostracoda, followed /Meldgaard and Knudsen 1979/. 13 samples in contiguous 10 cm intervals from 450 to 580 cm depth were analysed under microscope according to their content of calcareous fossils (Figure 3-2). Preparations were performed by FD Stefan Wastegård at the Department of Physical Geography and Quaternary Geology, Stockholm University.

3.6 Grain size distributions and carbonate content

Nine sub-samples were submitted to Sweco Geolab for determinations of grain size distributions and carbonate content. The sub-samples cover the following intervals: 40–48, 48–55, 60–70, 220–230, 343–350, 400–410, 450–460, 500–510 and 550–560 cm depth (Figure 3-2). Grain size distributions are reported following the standards SS027123 and SS027124. Carbonate contents were determined with Passon´s technique on material < 0.06 mm.

4 Methods

4.1 General

The methods used are according to the Activity Plan SKB AP PF 400-04-116.

4.2 Preparations

Diatom identification and ecological information of the noted taxa were extracted from the following reference literature: /Cleve-Euler 1951–1955, Mölder and Tynni 1967–1973, Tynni 1975–1980, Krammer and Lange-Bertalot 1986, 1988, 1991ab, Snoeijs 1993, Snoeijs and Balashova 1994, Snoeijs and Vilbaste 1994, Snoeijs and Potapova 1995, Snoeijs and Kasperoviciene 1996/.

4.3 Data handling/post processing

The results were treated in the computer program Tilia /Grimm 1991–1993, 1992/ and the diagrams were created in Tilia graph /Grimm 1992/. Coniss was applied in order to facilitate comparison between stratigraphically adjacent samples /Grimm 1987/.

In the diatom diagrams, the identified diatoms were grouped together according to ecological preferences, following mainly /Snoeijs 1993, Snoeijs and Balashova 1994, Snoeijs and Vilbaste 1994, Snoeijs and Potapova 1995, Snoeijs and Kasperoviciene 1996/:

Brackish-marine taxa are widespread in the Baltic Sea and decrease towards the north.

Baltic Sea taxa occur everywhere in the Baltic Sea.

Baltic Sea taxa with freshwater affinity are widespread in the Baltic Sea and decrease towards the south.

Freshwater taxa with Baltic Sea affinity occur in coastal waters throughout the Baltic Sea near freshwater discharges.

Freshwater taxa lives in e.g. lakes and streams and are considered as reworked in the present study. Some frustules could also be reworked from sediment accumulated in the Ancylus Lake.

Unknown ecology consists of genera not possible to identify to species level because of fragmentation and/or orientation in the slide.

4.4 Analyses and interpretations

The results from the analyses of siliceous microfossils are presented as a summary diagram with diatoms (excluding *Chaetoceros* spp resting spores), *Chaetoceros* spp resting spores, Tertiary taxa, Chrysophyte stomatocysts, the ebridian *Ebria tripartita*, the silicoflagellate *Dictyocha speculum*, sponge spiculae and phytoliths. The distribution of diatom taxa (excluding *Chaetoceros* spp resting spores) is partly shown as a summary diagram with the above mentioned groups partly as graphs for the individual diatom taxa (Appendix 1). The lower part of the sediment core is excluded for the latter diagrams because of low basic sums; instead this part is presented in Appendix 2. The results from Coniss have been applied for all diagrams, including organic carbon and accumulation of organic carbon/year.

Calibration of radiocarbon dates were performed with OxCal v.3.8. /Stuiver et al. 1998/. Calibrated dates are shown with 95.4% probability (± 2σ) on the left side of the summary diagrams. All dates of bulk sediment from the Baltic Sea contain a reservoir age. This can vary between c 200–1,000 years depending on sampling site and type of organic material imbedded in the sediment. At this sampling site an average age of 400 years has been subtracted before calibration /cf Olsson 1996, Hedenström and Possnert 2001/.

4.5 Nonconformities

The activity was conducted as planned without any nonconformities.

5 Results

The original results are stored in the primary data base SICADA, which are used for further interpretation. The data is traceable in SICADA by the Activity Plan number (AP PF 400-04-116).

The Baltic Sea basin has experienced several stages after the Weichselian deglaciation /Gudelis and Königsson 1979, Winterhalter 1988, Björck 1995, Björck and Svensson 2002/. The Baltic Ice Lake (c 15,000–11,500 cal. years BP) was first formed in the southern part of the basin, gradually extending towards the north as the ice front withdrawed. When the ice front passed the northern tip of Mt Billingen, the basin drained into the Atlantic, allowing topographic contact between sea level and the formation of the next stage of the Baltic, i.e. the Yoldia Sea (c 11,500–10,800 cal. years BP). This stage was short and ended when isostatic uplift cut off the connection. Since there was no contact with the sea, a new freshwater stage in the Baltic basin, i.e. the Ancylus Lake (c 10,800–9,500 cal. years BP), was established. As the climate improved global sea level rose rapidly causing a transgression in the Öresund/Store Bält area. When the sea entered the Baltic basin, gradually increasing brackish conditions were established in the Baltic basin and the Littorina Sea (c 9,500–0 cal. years BP) was formed. The salinity culminated c 5,000 years ago when the water depths at the thresholds in the south were largest /Westman et al. 1999/.

The lithology of the sediment core PFM004396 consists of clay in the lower part (Table 5-1). Organic content increases upwards resulting in accumulation of clay gyttja and/or gyttja clay. The uppermost part consists of sand.

The following problems arose during sub-sampling and preparation:

- White spots, that could be mould, were observed on one half of the core segments 130–185 cm and 300–385 cm. This entailed in sub-sampling for radiocarbon dating from the other halves.
- Dried laminated sediment 355–450 cm was easily crushed during sub-sampling, making it difficult to cut 1 cm slices.

Table 5-1. Lithology of the sediment core PFM004396, Forsmark. The uppermost 40 cm were not included in this sediment core.

Depth (cm)	Lithologic Unit	Description	Munsell
040–055	8	Silty sand, bluish/brownish from Fe-precipitation.	10Y 3/1
055–355	7	Silty clay gyttja/gyttja clay, greyish brown with organic concentrations at 112, 128, 142–144, 158, 162, 204, 214, 234, 293, 307, 337, 342 cm. Occasional gravel at 339 cm. Silty sequence at 342–350 cm.	5Y 3/2
355–431	6	Laminated gyttja clay, brownish grey.	5Y 4/1
431–455	5	Clay, grey. Lumps of brownish clay.	5Y 4/1
455–465	4	Clay with lime-drop stones, grey. Lumps of brownish clay.	5Y 4/1
465–535	3	Clay with occasional lime-drop stones, grey. Black (sulphide?) stained at 485–490 cm. Lumps of brownish clay.	5Y 4/1
535–580	2	Gyttja clay, grey. Lumps of brownish clay.	5Y 4/1
580–585	1	Lime ($CaCO_3$), light grey.	5Y 6/1

5.1 Chronology

The radiocarbon dating resulted in ages between 22,000 and 2,390 ^{14}C years (Appendix 3). The three lowermost dates are obviously too old and indicate a hiatus somewhere between 410 and 469 cm depth. These three dates are probably too old because of contamination from limestone with infinite age and/or incorporation of pre-Holocene organic material. It is plausible to assume that the hiatus is represented at the transition from clay to laminated clay gyttja at 431 cm depth. According to the diatom content the lower five lithologic units in Table 1 should have been deposited during the Yoldia Sea stage of the Baltic. The laminated sequence is likely from the Littorina Sea stage when bottom conditions have become calm enough to allow sedimentation. The lamina were caused by low oxygen concentrations at the bottom resulting in a lack of bioturbation /cf Burke et al. 2002/. Also the radiocarbon age at 410 cm depth, 6,890–6,660 cal yrs BP ($\pm 2\sigma$), indicates that deposition took place in the Littorina Sea /cf Witkowski et al. 2005/. The age at the top of the sediment core is 2,000–1,870 cal yrs BP, indicating that erosion prevails at the sampling site at present.

The sedimentation rate during the Littorina Sea stage is based on the assumption of continuous accumulation between c 7,000 and 2,000 cal yrs (Figure 5-1). This interval span from 0 to 431 cm depth indicating that 4,310 mm of sediment has accumulated during c 5,000 years, i.e. an average of c 0.9 mm/year. Following the various inclinations of the graph in Figure 5-1, three stages can be recognized. The accumulation rate in zones 2–6 is close to average, c 0.86 mm/year, while it increases in zones 7 and 8 (c 2.4 mm/year). After that it decreases abruptly to c 0.25 mm/year, whereafter no sediment is accumulated during the last c 2,000 years. The accumulation rate during the Yoldia Sea stage is not quantified but was much higher because of the close access to glacier melt water products.

Most radiocarbon dates show upwards younger ages. There is an exception with the dates Poz-10186 and Poz-10187, which are reversed (Figures 5-1 and 5-2). There is no overlap after calibration, indicating that the dated material has been reworked. This sequence contains several strata with concentrated organic material that could have been subject to movements by currents.

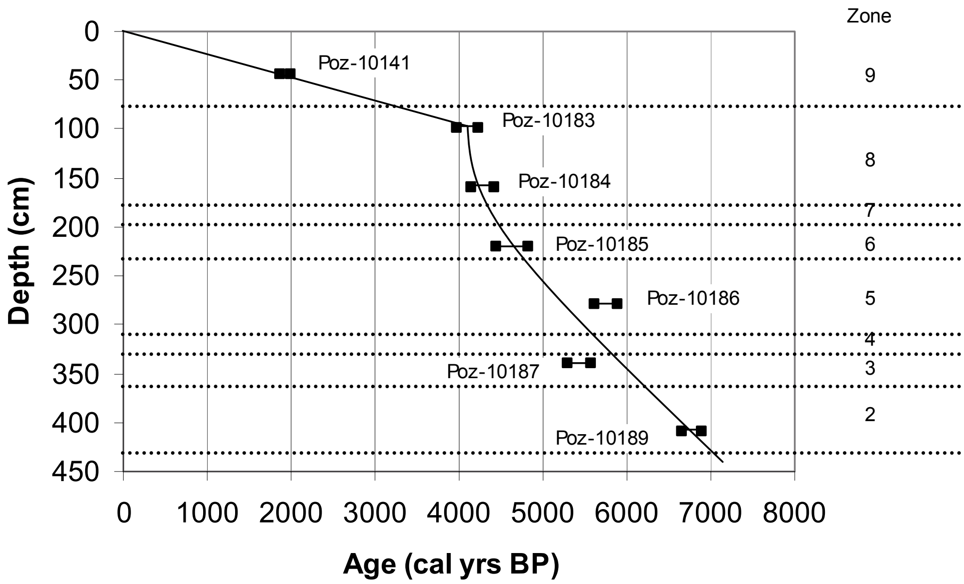

Figure 5-1. *Age-depth model. The ages are calibrated years before 1950, age intervals are stated with $\pm 2\sigma$.*

Atmospheric data from /Stuiver et al. 1998/; OxCal v3.8 (Bronk Ramsey 2002); cub r:4 sd:12 prob usp[chron]

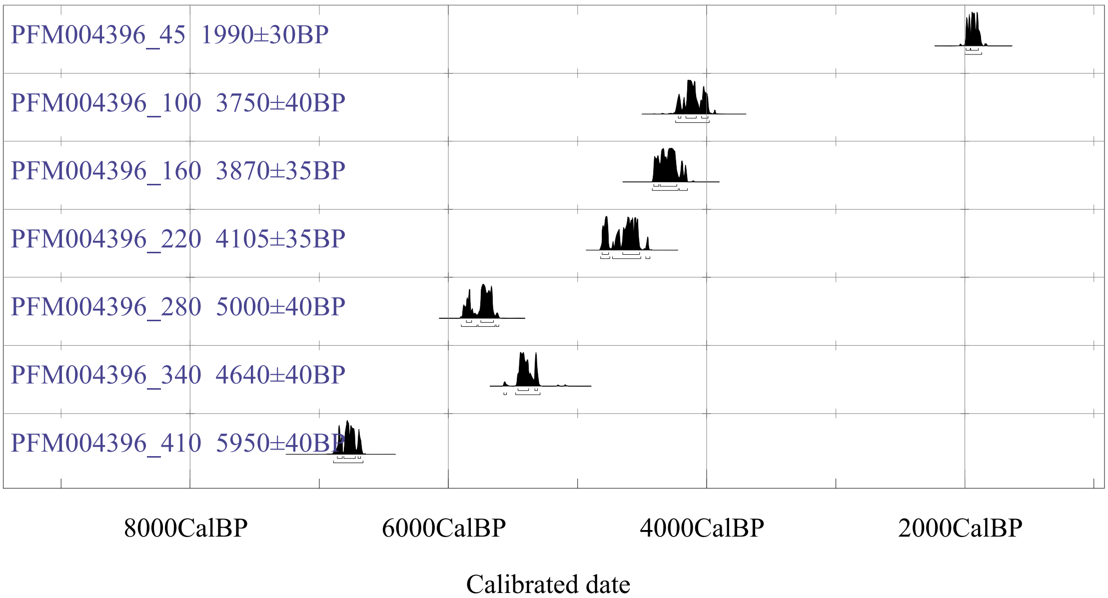

Figure 5-2. *Calibration of the uppermost seven radiocarbon dates according to /Stuiver et al. 1998/. Details of the dates are shown in Appendix 3.*

5.2 Siliceous microfossils

The diagrams showing the results from the analyses of siliceous microfossils have been divided into nine zones based on Coniss and the stratigraphic distribution of diatoms (Figures 5-3 and 5-4). Basic sums for the diatom diagram vary between 100 and 434 frustules for each analysed level. These numbers exclude *Chaetoceros* spp resting spores, which show mass occurrences in almost all samples (except in zone 1, /cf Risberg 1990, Miller and Risberg 1990/). When all types of siliceous microfossils are considered, the basic sums vary between 37 and 6,000. The observed siliceous microfossils include diatoms (including Tertiary taxa /cf Robertsson 2004/ in zone 1), Chrysophyte stomatocysts, *Ebria tripartita*, *Dictyocha speculum* (in zone 6), sponge spiculae (in zones 1, 5 and 9) and phytoliths (in zones 1 and 9).

Zone 1 (585–435 cm depth, c 11,000 cal years BP) is characterised by low abundances of all types of siliceous microfossils (cf Figure 5-3, Appendix 2). Dominating taxa includes e.g. *Chaetoceros* spp resting spores, *Grammatophora marina*, *Rhabdonema arcuatum*, *Psuedosolenia calcar-avis* (brackish-marine taxa), *Achnanthes taeniata*, *Thalassiosira decipiens*, *Th. hyperborea* v. *lacunosa* (Baltic Sea taxa), together with *Ctenophora fasciculata* and *Epithemia turgida* (Baltic Sea taxa with freshwater affinity). Also a few freshwater taxa were noted; *Amphora inariensis*, *Fragilaria capucina* and *Gomphonema* sp. The fragmentation of diatom frustules is high, indicating a high energy sedimentary environment. Tertiary taxa consist of unidentified fragments and an observation of a frustule from *Paralia sulcata* v. *biseriata* /cf Tynni 1982, Plate 1/ at 578 cm depth. Together with the sediment composition and the unreasonably old radiocarbon dates this zone is interpreted to represent sedimentation during the Yoldia Sea stage of the Baltic /cf Björck 1995/. This interpretation is supported by the occurrence of Tertiary taxa, which points at sediment originating from glacial melt water /cf Sandgren et al. 1999/. Furthermore, typical diatom taxa living in the oligotrophic water of the Ancylus Lake are missing (e.g. *Aulacoseira islandica*, *Stephanodiscus neoastraea*, *Gyrosigma attenuatum*).

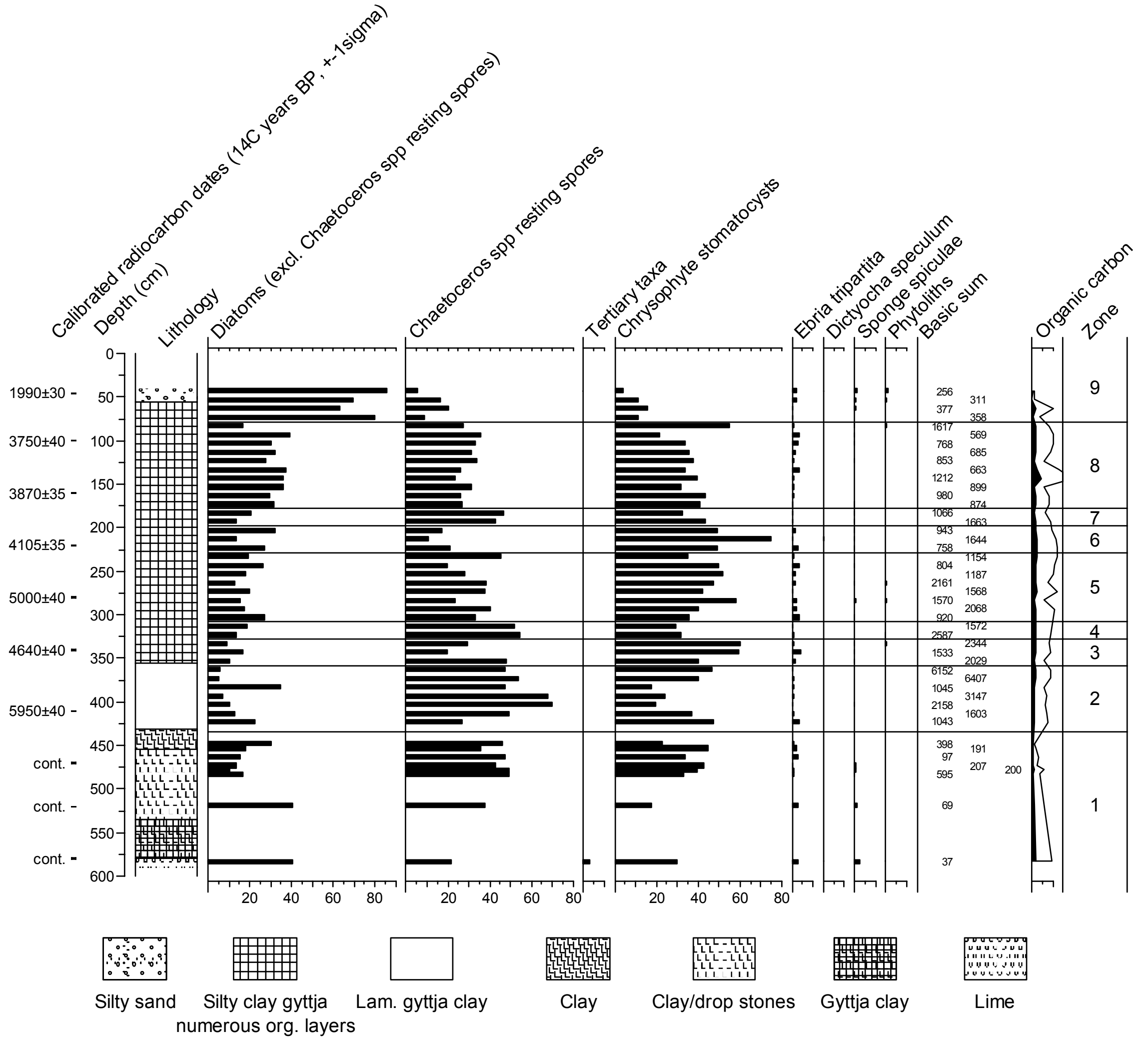

Figure 5-3. *Distribution of different groups of siliceous microfossils in core PFM004396. Only samples with relatively high abundances have been included in zone 1 (for details see Appendix 2). Probably there is a hiatus at the boundary between zone 1 and 2. Organic carbon is shown as percentages (solid area) and five times magnification (stippled area). The ages on the left-hand side of the diagram are calibrated radiocarbon dates. "cont." indicates position of dates, which are obviously too old (cf text and Appendix 3).*

Zones 2–9 are interpreted to reflect accumulation during the Littorina Sea stage, which further indicates that sediment from the Ancylus Lake stage is missing. Also sediment from the initial stage of the Littorina Sea is missing (c 9,500–7,000 cal years BP). The number of diatoms increases notably in zone 2 (435–358 cm depth, c 7,000–6,200 cal. years BP), being dominated by *Thalassiosira decipiens*. Other common taxa include *Cyclotella choctawhatcheeana*, *Psuedosolenia calcar-avis* and, in the lowest sample, *Thalassionema nitzschoides*. In zone 3 (358–328 cm depth, c 6,200–5,800 cal. years BP) *C. choctawhatcheeana* and *Th. decipiens* almost disappear, instead *Grammatophora marina*, *Hyalodiscus scoticus*, *Rhabdonema minutum* and *Th. hyperborea* v. *lacunosa* increases. Zone 4 (328–308 cm depth, c 5,800–5,500 cal. years BP) is characterised by very high percentages of *Achnanthes taeniata*, a taxon highly associated with sea-ice

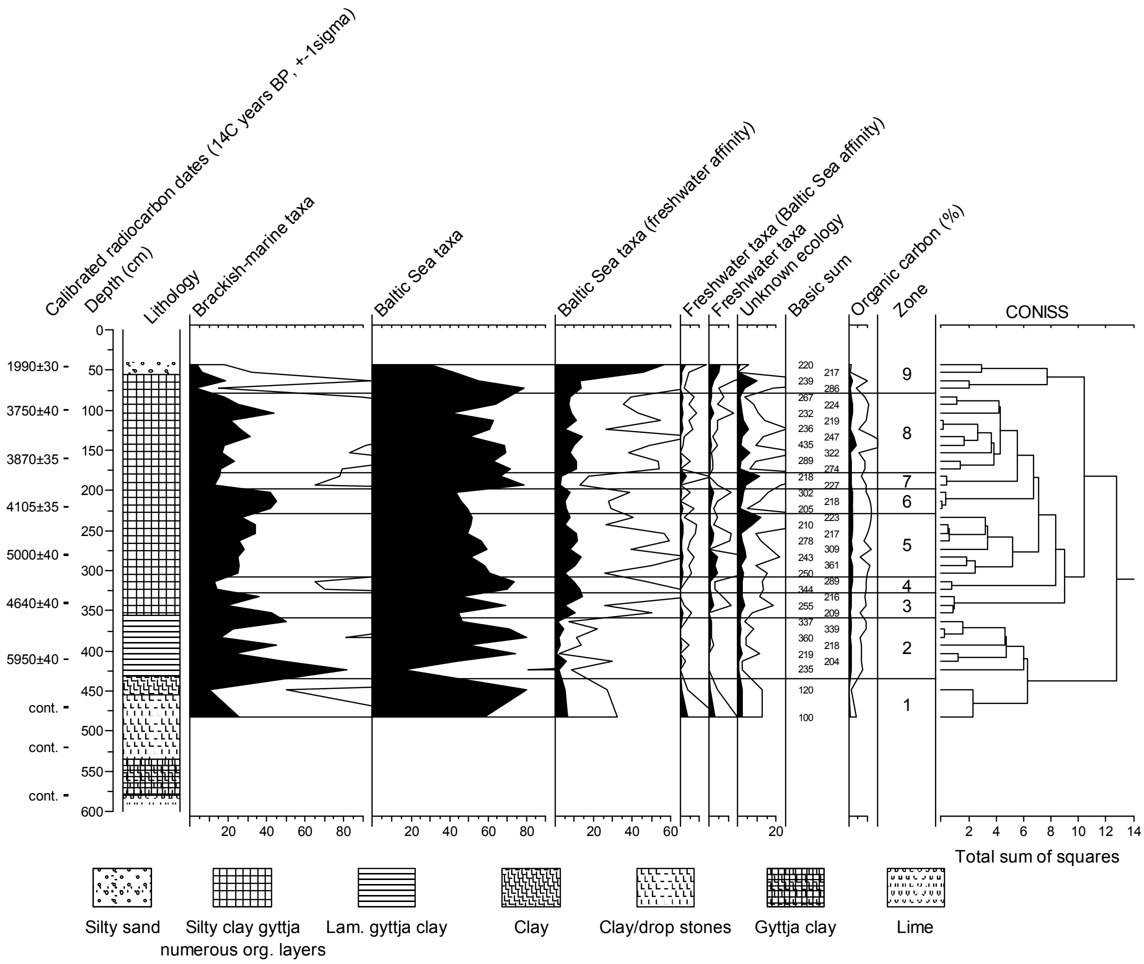

Figure 5-4. Grouping of diatoms in core PFM004396. Organic carbon is shown as percentages (solid area) and five times magnification (stippled area). Zone 1 is interpreted to represent sediment accumulation in the Yoldia Sea. Zones 2–9 represent sedimentation in the Littorina Sea. Details of the diatom distribution in zone 1 can be found in Appendix 2. The ages on the left-hand side of the diagram are calibrated radiocarbon dates. "cont" indicates position of dates, which are obviously too old (cf text and Appendix 3).

/Müller-Haeckel 1985, Syvertsen and Hasle 1988/ and early blooming /Höglander et al. 2004/. This species was found to be very common in the uppermost layers of sediment in the Gulf of Finland and decreasing towards the south where salinity is higher /Hällfors and Niemi 1975/. Zone 5 (308–228 cm depth, c 5,500–4,800 cal. years BP) is again dominated by *C. choctawhatcheeana*. Also *Fragilariopsis cylindrus* displays a small peak. Zone 6 (228–198 cm depth, c 4,800–4,400 cal. years BP) exhibits similarities with zone 3, i.e. *G. marina*, *H. scoticus* and *Rh. minutum* dominate. Zone 7 (198–178 cm depth, c 4,400–4,200 cal. years BP) consists of only two samples dominated by *Th. nitzschoides* and *Th. decipiens*. Zone 8 (178–78 cm depth, c 4,200–3,200 cal. years BP) is characterised by somewhat increased percentages of *Rhoicosphaenia curvata* and *Fragilaria fasciculata*. In Zone 9 (78–0 cm depth, c 3,200–2,000 cal. years BP), *Epithemia turgida* increases together with *Rh. curvata*. Most brackish-marine taxa decrease in favour of Baltic Sea taxa with a freshwater affinity and strict freshwater taxa.

The time involved for accumulation of sediment representing zones 2–9 span approximately the interval 7,000–2,000 cal yrs BP (5,000–0 cal yrs BC). According to /Westman et al. 1999/ the sea level in the Öresund Straight was at least 2 m above the present level at 7,000 cal yrs BP. This means that salinity should have been somewhat enhanced, as compared with today, when sediment started to accumulated after the interruption during the Ancylus Lake stage (and also the beginning of the Littorina Sea stage). The maximum level in the Öresund Straight was reached between 6,000 and 5,500 cal yrs BP when sea level was 3–4 m above present day level. The Darss Sills in the south was flooded approximately 1,000 years earlier /cf Witkowski et al. 2005/. At about 4,500 cal yrs BP the inflow via Darss Sills came to the present day situation, contemporary with efficient inflow via the Öresund Straight. This means that the highest salinity should be expected between 7,000–4,500 cal yrs BP in the analysed core /cf Lampe and Janke 2004, Borówka et al. 2005/.

The stratigraphic variations between zones 2–9 are in general relatively small. There is a weak trend of enhanced salinity in zones 2–6, corresponding to a situation with extensive inflow of marine water via the Swedish/Danish straights between 7,000–4,500 cal yrs BP. The uppermost zones 7–9 seem to indicate somewhat lower salinities. Besides changes in salinity, the diatom variations could also be influenced by re-directions in bottom currents and/or sea ice conditions.

The diatom composition of zone 9 indicates the lowest salinity. This is probably the result from the reduction of saline inflow through the Öresund Straight /Westman et al. 1999/ and the regressive shore displacement /cf Hedenström and Risberg 2003/. The latter will cause a more efficient input of freshwater taxa from nearby river mouths.

5.3 Calcareous fossils

Despite the scattered occurrences of brackish water living diatoms, no observations of foraminifera or Ostracoda were made in the sediments accumulated in the Yoldia Sea (zone 1). This could probably be explained by relatively low salinity, cold water and/or high accumulation rate /Schoning 2001/. On the other hand the carbonate content is relatively high in the analysed sediment, why the preservation conditions for calcaereous fossils should be favourable.

5.4 Organic carbon

The amount of organic carbon is fluctuating and relatively low, varying between 0.1 and 4.2% (Figure 5-5). The lowest values are recorded at the top of zone 1 and at the top of zone 9. In zone 1 there is a decreasing trend towards the top. The reason for this decrease is not fully understood but could result from variations in the melt water streams from the Weichselian ice sheet. The relatively high numbers may be explained by incorporation of reworked older organic material (cf the old ages of the radiocarbon dates). The organic carbon content rises abruptly above the hiatus at 431 cm depth, i.e. at the transition to the Littorina Sea stage. After that a general gradual increase is observed throughout zones 2 to 5. It is likely that this interval spans the time period with the highest salinity (7,000–4,500 cal yrs BP) during the postglacial climate optimum. Thus the organic

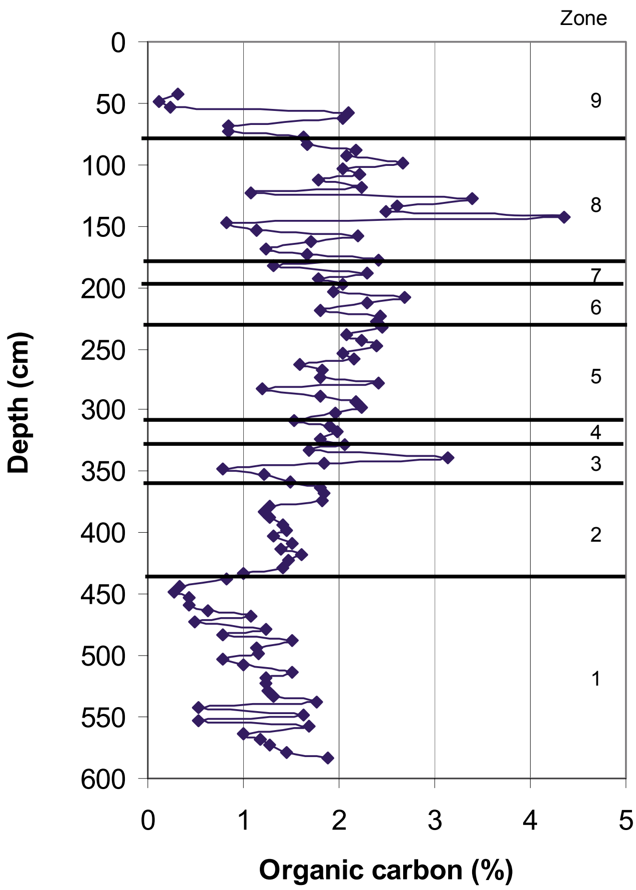

Figure 5-5. *Graph showing the variations in organic carbon in core PFM004396. The zonation is based on Coniss from the diatom analysis. Note the decreasing trend in zone 1. The highest values are recorded in zone 8. The boundary between zone 1 and 2 represent a c 4,000 year long hiatus. Zone 1 represents sedimentation in the Yoldia Sea and zones 2–9 in the Littorina Sea.*

carbon production on land and in the water mass was at its highest. Zones 6–8 display slightly decreasing and similar values, probably because of a climate deterioration. The gradually decreasing distance to the surrounding shore lines, caused by a regressive shore line, will cause more fluctuating values. The uppermost part of zone 9 reveals decreasing organic carbon values, mainly because of accumulation of sand, i.e. the sampling site has changed character from an accumulation bottom to an erosive bottom /cf Håkansson and Jansson 1983/.

Since the sampling volumes varied, it was not possible to calculate numbers for the accumulation rate of organic carbon/cm^2/year. An attempt was made, however, to estimate the accumulation of organic carbon per year (Figure 5-6). Also these numbers (c 15–35 mg C/yr) will vary considerably because of different sampling intervals (due to sporadic desiccation). The numbers were calculated as follows: dry weight (g) x org. C (%) x 100/11. It was assumed that each sample represented 1 cm of sediment. With an average accumulation rate of 0.9 mm/year, every cm of sediment will represent 11 years. Despite the above uncertainties, there is a general trend of slightly increasing accumulation rates from the initial Littorina Sea stage upwards (zone 2–5). This trend changes at the transition between zone 5 and 6 where accumulation rates start to decrease.

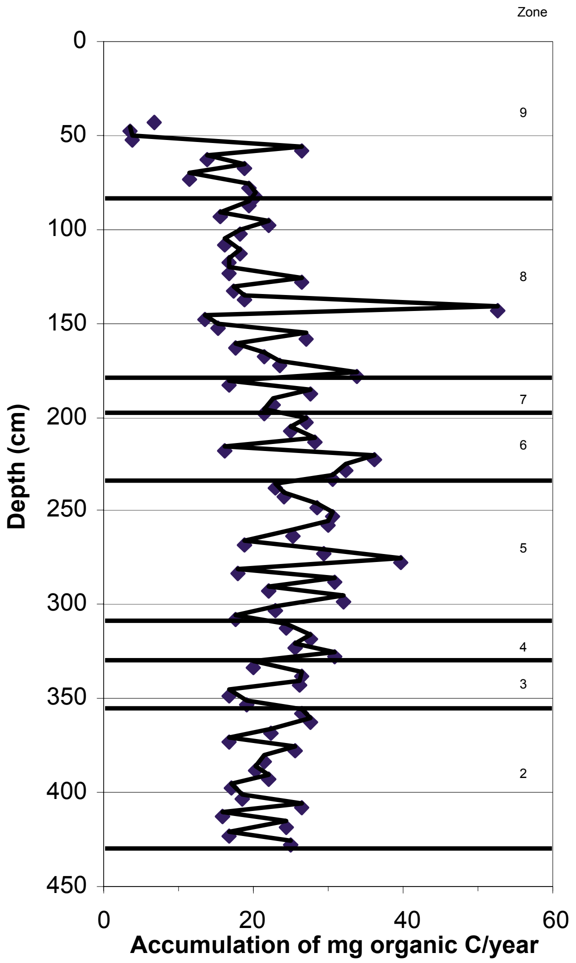

Figure 5-6. *Accumulation of mg organic carbon/year. The general increasing trend is likely the result of the climate amelioration during the Holocene.*

5.5 Grain size distributions and carbonate content

The content of clay, silt, sand, $CaCO_3$, organic carbon and the classification are reported in Table 5-2. Sedimentation in diatom zone 1, i.e. the Yoldia Sea, was dominated by clay also described from investigations of lake sediment in the Forsmark area /Hedenström 2004/. The sand fraction increases in the sediment accumulated in the Littorina Sea. This is probably caused by the increasing proximity to land allowing coarser particles to reach the sampling site.

Table 5-2. The content of clay, silt, sand, $CaCO_3$ and organic carbon together with the classification of nine samples from core PFM004396. Clay and silt contents were not calculated for the samples 048–055 and 450–460 cm because of flocculation during sedimentation.

Sample depth (cm)	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	Approx. org. C (%)	Classification	Diatom zone	Baltic Sea stage
040–048	6	32	62	0	0.2	Clayey silty sand	9	Littorina Sea
048–055	–	–	62	0	0.1	Silty sand	9	Littorina Sea
060–070	15	53	32	1	2.0	Gyttja clayey silt	9	Littorina Sea
220–230	24	70	6	0	2.4	Gyttja clay	6	Littorina Sea
343–350	30	51	19	0	1.5	Clay (medium)	3	Littorina Sea
400–410	14	82	4	1	1.4	Clayey silt	2	Littorina Sea
450–460	–	–	4	0	0.3	Clay (stiff)	1	Yoldia Sea
500–510	80	20	0	5	1.0	Clay (stiff)	1	Yoldia Sea
550–560	73	27	0	11	1.5	Clay (stiff)	1	Yoldia Sea

6 Summary and discussions

Despite poor storage conditions the achieved results seem not to be have been affected in a serious way. A compilation of the results from this activity is presented in Figure 6-1. The lithology of the analysed core is similar to several other cores from the Baltic basin /e.g. Westman and Sohlenius 1999/ with the exception of a hiatus during the Ancylus Lake stage. A hiatus at the corresponding stratigraphical level was observed in a core collected and analysed in the archipelago above the tunnel between Äspö Island and Simpevarp nuclear power plant /Risberg 2002/. Also this core contained clay accumulated in the Yoldia Sea underlying Littorina Sea sediment. Accumulation started, however, earlier offshore Forsmark, probably because of more favourable local conditions.

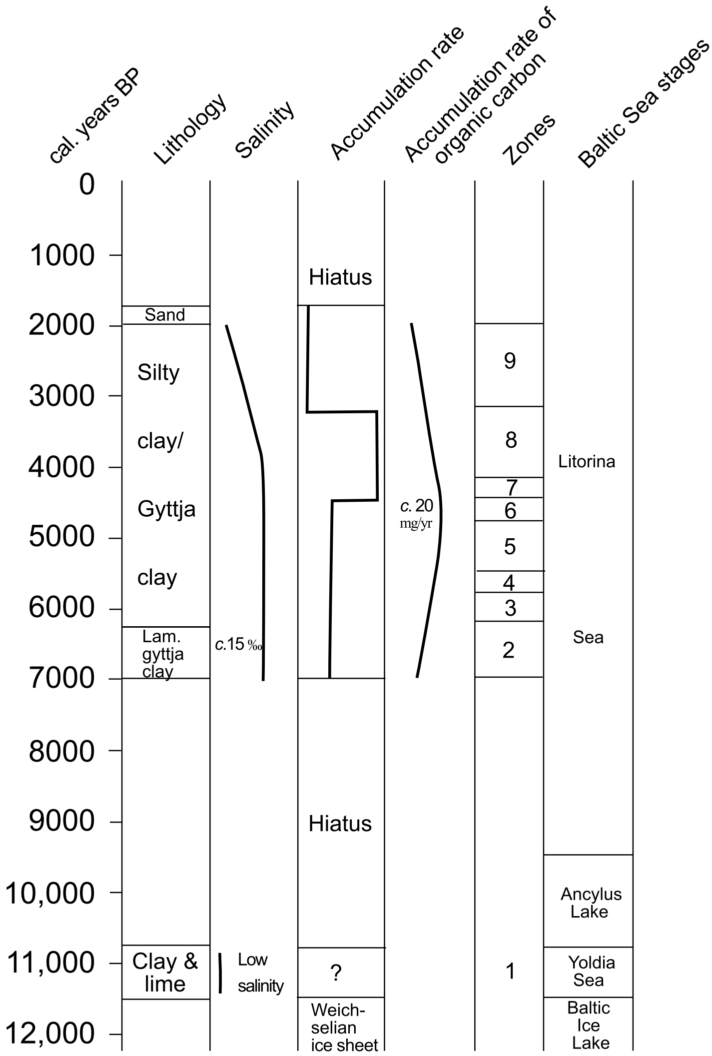

Figure 6-1. Compilation of data achieved from sediment core PFM004396. The age scale in relation to the simplified lithology is based on the age-depth model shown in Figure 5-1. The salinity variations should be regarded as rough estimates. The zonation is based on Coniss from the diatom diagrams.

Sedimentation during the Littorina Sea consisted of clay gyttja/gyttja clay which appears more or less laminated. The formation of laminated sediment during the early Littorina stage has been reported by e.g. /Burke et al. 2002/. This was caused by aerobic conditions at the bottom because of a stratified water mass with high salinity water at the bottom and lighter water at the top. This caused oxygen to be consumed, resulting in an extinction of the biologic life. A similar feature is caused today as a combined effect from high nutrient input and poor mixing /cf Jonsson et al. 1999/.

Despite the regressive shore displacement, the analysed core was collected in an area that will remain under water also at AD 5,000 /Brydsten 1999/.

The purposes stated under objective and scope are answered as follows:

- Salinity during the Yoldia Sea stage was low since no finds of calcareous fossils were made. The highest salinity prevailed between 7,000 and 4,500 cal yrs BP. The exact per mille is difficult to estimate but should lay around 15‰.
- Zone 1 represents sedimentation in the Yoldia Sea with an unknown accumulation rate. Zones 2-9 represent sedimentation in the Littorina Sea with a continuous accumulation between 7,000 and 2,000 cal yrs BP.
- Sediment was either not accumulated during the Ancylus Lake stage and the beginning of the Littorina Sea stage (c 10,500–7,000 cal yrs BP) or eroded later. A second erosive phase is prevailing from c 2,000 cal yrs BP until present.
- The average accumulation rate during the Littorina Sea stage was c 0.9 mm/year.
- The accumulation rate of organic carbon varies between 15 and 35 mg C/year. There are increasing trends from zone 2 until zone 5, where a general decrease starts. In time this corresponds to c 4,500 cal yrs BP.
- The sediment is characterised by a high degree of clay particles. It is only in the uppermost c 50 cm that sand particles dominate. Carbonate contents are low except in the lowermost samples where 5 and 11% were measured.

Acknowledgement

Anna Hedenström, Swedish Geological Survey/SKB initiated activity and read the manuscript. Päivi Kaislahti Tillman assisted with laboratory work, Tomasz Goslar performed the radiocarbon datings and Stefan Wastegård carried out the analyses for calcareous fossils.

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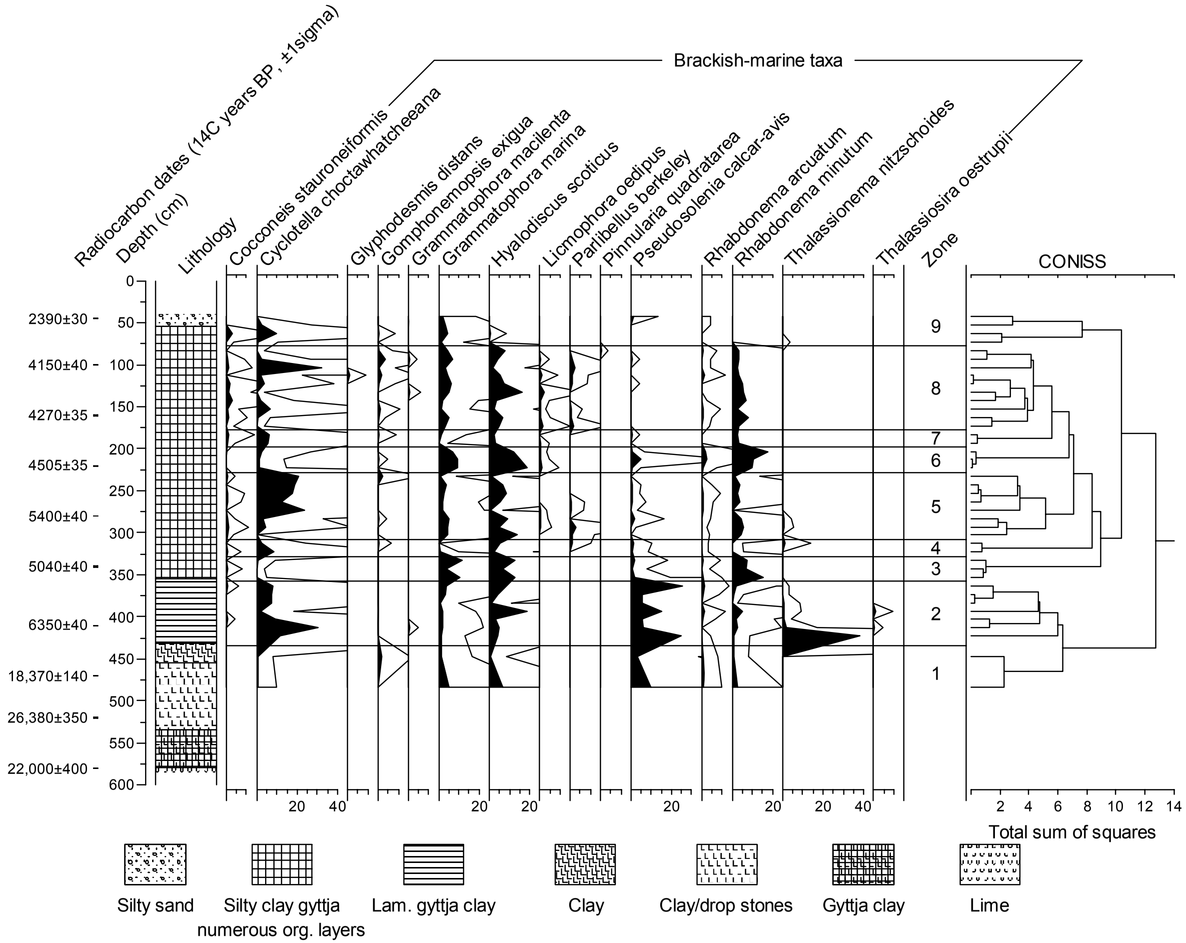
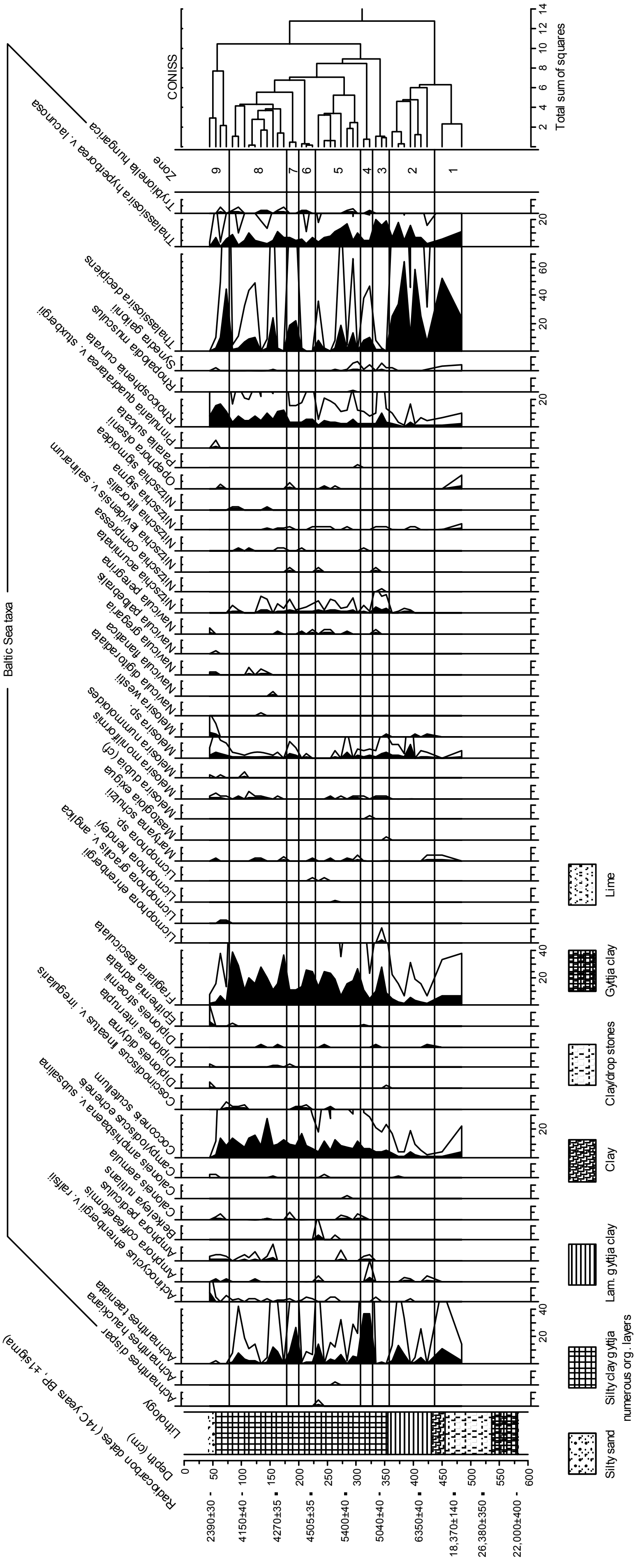
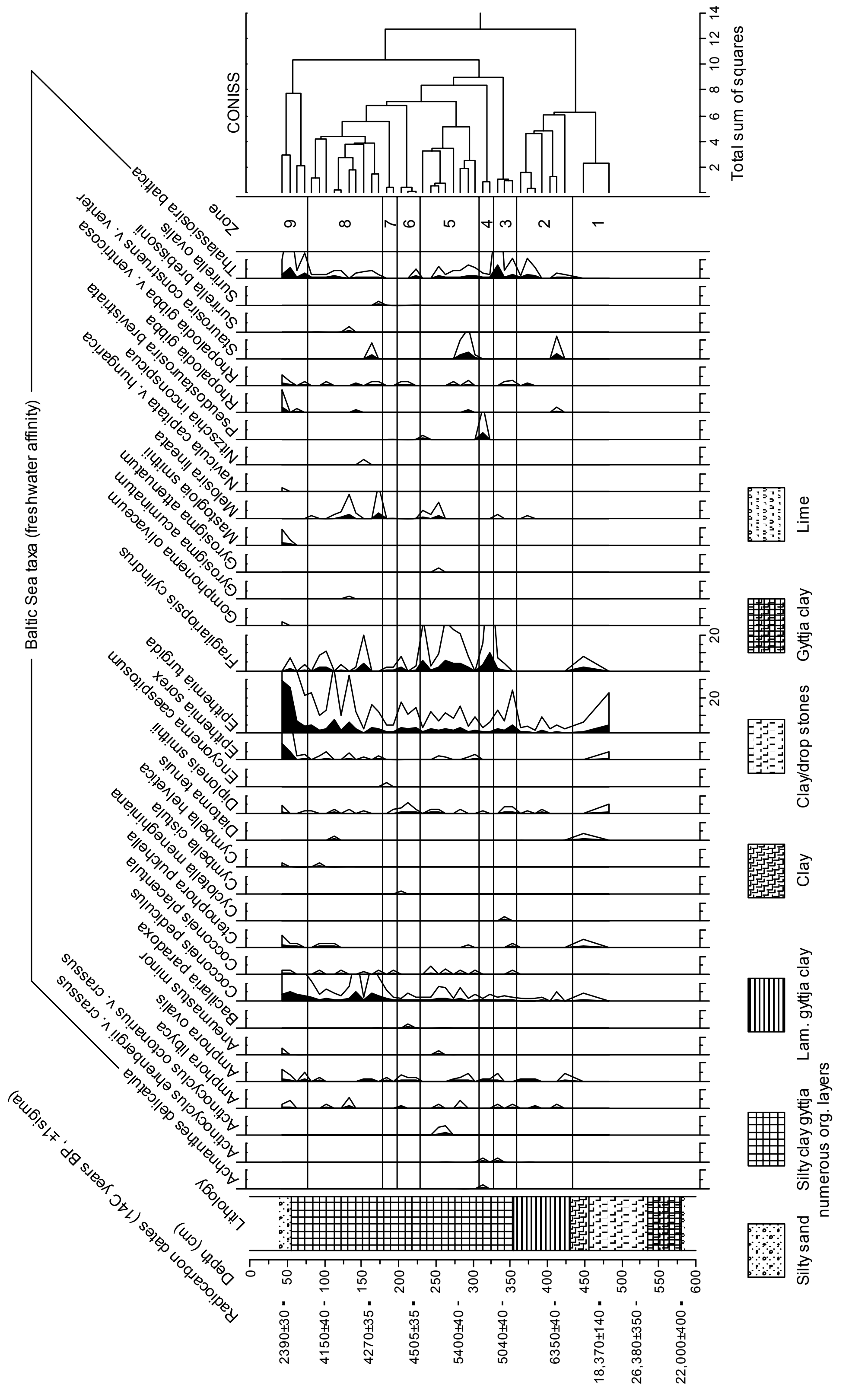
Appendix 1

Stratigraphic distribution of diatom taxa in sediment core PFM004396. Calibrated ages can be found in Appendix 3. Solid areas represent percent while shaded areas represent permille

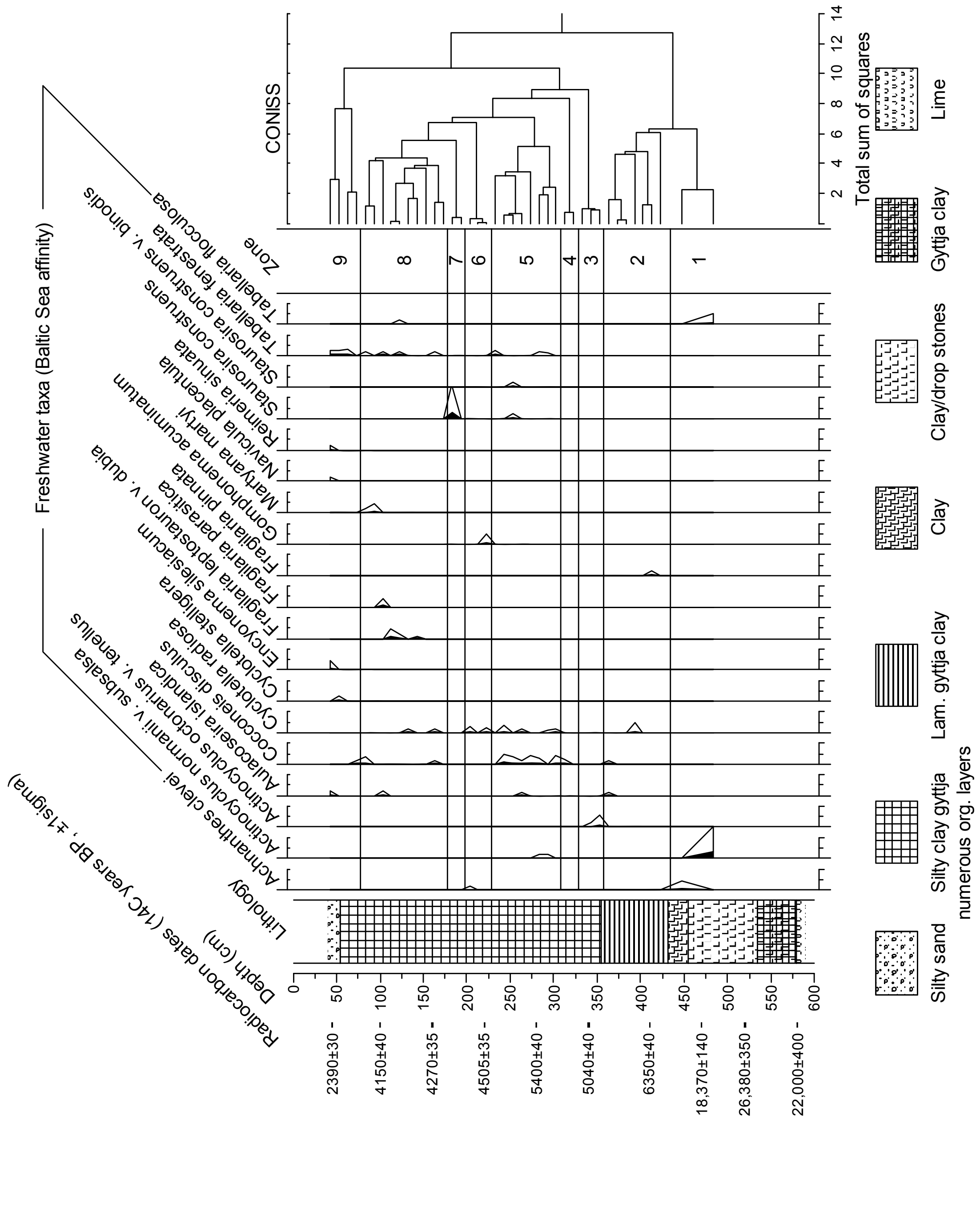




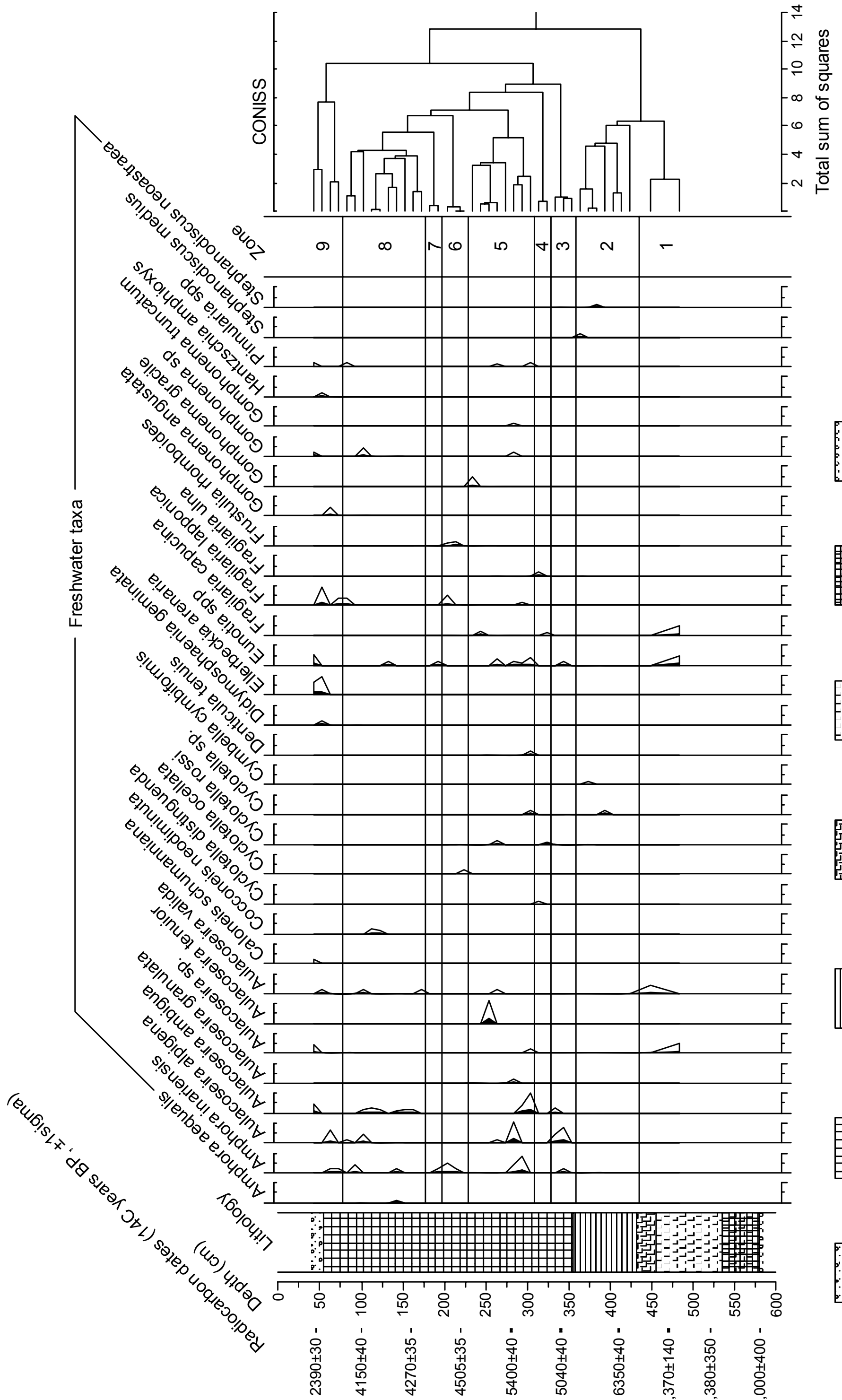
CONISS
Total sum of squares
Zone
1 2 3 4 5 6 7 8 9
Baltic Sea taxa
Lithology
Depth (cm)
Radiocarbon dates (14C years BP, ±1 sigma)
2390±30
4150±40
4270±35
4505±35
5400±40
5040±40
6350±40
18,370±140
26,380±350
22,000±400
Silty sand
Silty clay gyttja numerous org. layers
Lam. gyttja clay
Clay
Clay/drop stones
Gyttja clay
Lime



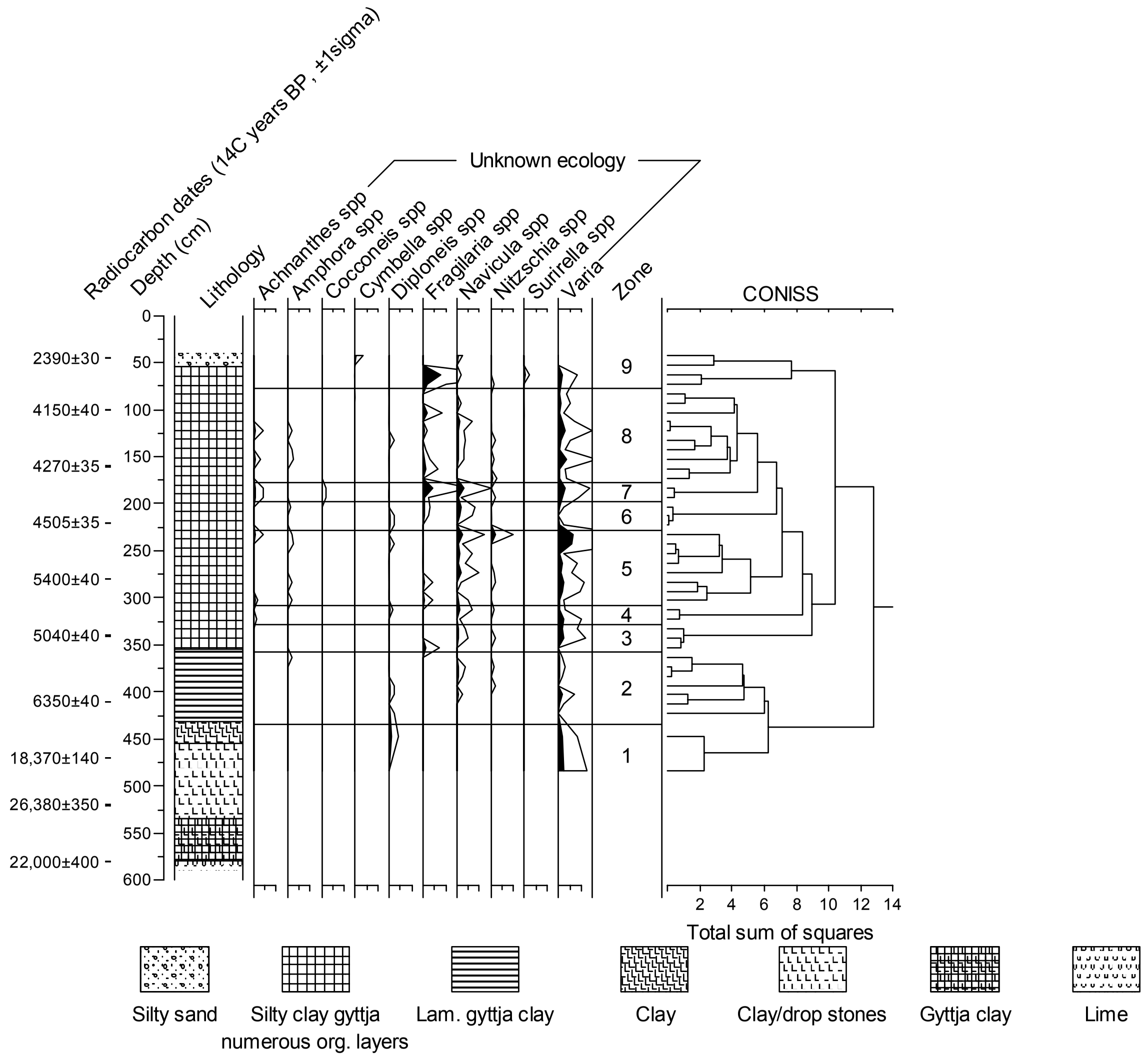
Baltic Sea taxa (freshwater affinity)
CONISS
Total sum of squares
Zone
Lithology
Depth (cm)
Radiocarbon dates (14C years BP, ±1sigma)
Achnanthes delicatula
Actinocyclus ehrenbergii v. crassus
Actinocyclus octonarius v. crassus
Amphora libyca
Amphora ovalis
Aneumastus minor
Bacillaria paradoxa
Cocconeis pediculus
Cocconeis placentula
Ctenophora pulchella
Cyclotella meneghiniana
Cymbella cistula
Diatoma tenuis
Diploneis smithii
Encyonema caespitosum
Epithemia sorex
Epithemia turgida
Fragilariopsis cylindrus
Gomphonema olivaceum
Gyrosigma acuminatum
Gyrosigma attenuatum
Mastogloia smithii
Melosira lineata
Navicula capitata v. hungarica
Nitzschia inconspicua
Pseudostaurosira brevistriata
Rhopalodia gibba
Rhopalodia gibba v. ventricosa
Staurosira construens v. venter
Surirella brebissonii
Surirella ovalis
Thalassiosira baltica
2390±30
4150±40
4270±35
4505±35
5400±40
5040±40
6350±40
18,370±140
26,380±350
22,000±400
Silty sand
Silty clay gyttja numerous org. layers
Lam. gyttja clay
Clay
Clay/drop stones
Gyttja clay
Lime



Freshwater taxa (Baltic Sea affinity)
Radiocarbon dates (14C years BP, ±1sigma)
Depth (cm)
Lithology
Achnanthes clevei
Actinocyclus normanii v. subsalsa
Actinocyclus octonarius v. tenellus
Aulacoseira islandica
Cocconeis disculus
Cyclotella radiosa
Cyclotella stelligera
Encyonema silesiacum
Fragilaria leptostauron v. dubia
Fragilaria parasitica
Fragilaria pinnata
Gomphonema acuminatum
Martyana martyi
Navicula placentula
Reimeria sinuata
Staurosira construens
Staurosira construens v. binodis
Tabellaria fenestrata
Tabellaria flocculosa
Zone
CONISS
Total sum of squares
2390±30
4150±40
4270±35
4505±35
5400±40
5040±40
6350±40
18,370±140
26,380±350
22,000±400
Silty sand
Silty clay gyttja numerous org. layers
Lam. gyttja clay
Clay
Clay/drop stones
Gyttja clay
Lime



Freshwater taxa
Zone
CONISS
Total sum of squares
Lithology
Depth (cm)
Radiocarbon dates (14C years BP, ±1sigma)
2390±30
4150±40
4270±35
4505±35
5400±40
5040±40
6350±40
18,370±140
26,380±350
22,000±400
Silty sand
Silty clay gyttja numerous org. layers
Lam. gyttja clay
Clay
Clay/drop stones
Gyttja clay
Lime



Radiocarbon dates (14C years BP, ±1sigma)
Depth (cm)
Lithology
Achnanthes spp
Amphora spp
Cocconeis spp
Cymbella spp
Diploneis spp
Fragilaria spp
Navicula spp
Nitzschia spp
Surirella spp
Varia
Unknown ecology
Zone
CONISS
2390±30
4150±40
4270±35
4505±35
5400±40
5040±40
6350±40
18,370±140
26,380±350
22,000±400
0
50
100
150
200
250
300
350
400
450
500
550
600
9
8
7
6
5
4
3
2
1
2
4
6
8
10
12
14
Total sum of squares
Silty sand
Silty clay gyttja
numerous org. layers
Lam. gyttja clay
Clay
Clay/drop stones
Gyttja clay
Lime

Appendix 2

Observations of siliceous microfossils in zone 1 in PFM004396. f = fragment, g.b. = girdle band

Depth (cm):	583	578	573	563	558	553	543	538	533	523	518	513	503	498	493	483	478	473	463	453	448	443	438	433
Brackish-marine taxa																								
Chaetoceros spp resting spores	8				1						26	1			1	301	98	89	46	68	183	3	3	
Cocconeis stauroneiformis											1													
Coscinodiscus spp	3 f.						1 f.				1 f.					2 f.								
Cyclotella choctawhatcheeana											1					1					1			
Gomphoneopsis exigua																					2			
Grammatophora marina											2 + 3 g.b.				1	4.5	1 + 3g.b.	3 + 1g.b.	3 + 1g.b.	3 + 2g.b.	1+ 1 g.b.			
Hyalodiscus scoticus			1								3					6.5	1.5	1	1.5	1.5	1			
Melosira arctica											1													
Parlibellus berkeley																		1						
Pseudosolenia calcar- avis											2					10		3	2	4	4	1		
Rhabdonema arcuatum											3 g.b.					10 g.b.	7 g.b.	9 g.b.	0.5 + 14 g.b.	0.5 + 17 g.b.	11 g.b.	2 g.b.		
Rhabdonema minutum											2					2.5		1			1			
Thalassionema nitzschoides																				1				
Baltic Sea taxa																								
Achnanthes taeniata																3		1			13.5			
Actinocyclus ehrenbergii v. *ralfsii*											1						0.5 + 1 f.							
Cocconeis scutellum											2					4.5		2.5			0.5			
Diploneis stroemii											0.5													

Depth (cm):	583	578	573	563	558	553	543	538	533	523	518	513	503	498	493	483	478	473	463	453	448	443	438	433
Licmophora nubecula																	1							
Martyana schulzii										0.5											1			
Melsoira sp.																0.5			1	3				
Navicula crucicula															1									
Nitzschia acuminata																		1						
Nitzschia sigma																f								
Opephora olsenii																2								
Rhoicosphaenia curvata	1															4					1.5			
Synedra gailonii																0.5					1 f.			
Thalassiosira decipiens																24	1	3		2	63			
Thalassiosira hyberborea v. *lacunosa*	0.5 + 5 f.										1					12	1.5	1.5	2	3 + 1 f.	7.5 + 2 f.	0.5	1 f.	
Baltic Sea taxa (freshwater affinity)																								
Actinocyclus ehrenbergii v. *crassus*											1													
Amphora libyca																		1						
Cocconeis pediculus																		0.5			1			
Ctenophora fasciculata	7									1 + 1 f.	5 + 18 f.	1 f.	1 f.		1 + 3 f.	7.5 + 40 f.	5.5 + 11 f.	3 + 16 f.	0.5 + 7 f.	5.5 + 18 f.	8 + 30 f.	3 f.	0.5 + 2 f.	3 f.
Ctenophora pulchella																					1			
Diatoma tenuis																					1			
Diploneis smithii																0.5						0.5		
Epithemia sorex																1								
Epithemia turgida + v. *westermanni*	7 f.										2.5 + 2 f.					4.5 + 10 f.	1.5 + 3 f.	0.5 + 3 f.	0.5 + 2 f.	1.5 + 8 f.	1.5 + 4 f.	1 + 1 f.		
Fragilariopsis cylindrus																				1	2			
Gomphonema olivaceum	1																							
Gyrosigma attenuatum																								1

Depth (cm):	583	578	573	563	558	553	543	538	533	523	518	513	503	498	493	483	478	473	463	453	448	443	438	433
Melosira lineata																				1		1		
Navicula lanceolata																				1				
Thalassiosira baltica											1						0.5		0.5	1 f.				
Freshwater taxa (Baltic Sea affinity)																								
Achnanthes clevei																					0.5			
Actinocyclus normanii v. *subsalsa*																3	0.5							
Aulacoseira islandica											0.5									1				
Tabellaria flocculosa																g.b.								
Freshwater taxa																								
Amphora inariensis																				2				
Aulacoseira valida															1						1			
Aulacoseira sp.																1								
Eunotia incisa																1								
Fragilaria capucina																1								
Fragilaria ulna																				1 f.				
Gomphonema sp.																	1	1						
Pinnularia spp	3 f.						1 f.																	1 f.
Unknown ecology																								
Diploneis sp.																					0.5			
Navicula spp	1 f.																							
Varia	3 f.										20 f.		2 f.		3 f.	70 f.	25 f.	12 f.	10 f.	1 + 23 f.	2 + 20 f.	3 f.	1 f.	3 f.
Tertiary taxa																								
Unidentified	4 f.	1 f.				1 f.																		

Depth (cm):	**583**	**578**	**573**	**563**	**558**	**553**	**543**	**538**	**533**	**523**	**518**	**513**	**503**	**498**	**493**	**483**	**478**	**473**	**463**	**453**	**448**	**443**	**438**	**433**
Paralia sulcata v. *biseriata*		1																						
Basic sum	24	2	1	0	1	1	2	0	0	2.5	55	2	2	0	6	22	117	116	59	103	214	10	6	4
Phytoliths											1											1		
Chrysophyceae stomatocysts	11				1			2			57	1	1		3	195	81	88	33	85	91	5	7	2
Sponge spiculae	0.5 + 3 f.	1 f.					1 f.	1 f.		1 f.	1 f.		2 f.			1 f.	0.5	0.5						
Ebria tripartita	1										2					5	2	1	3	4	3			
Basic sum	35	3	1	0	2	1	3	3	0	3.5	116	3	4	0	9	81	201	205	95	192	287	16	13	6
No of traverses/slides	12	3/4	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	3/4	1/2	1/2	1/2	1/2	11	3/4	1/2	1/1	3/4	10	1/2	1/2	1/2
Magnification	1,000	400+ 1,000	400+ 1,000	400+ 1,000	400+ 1,000	400+ 1,000	400+ 1,000	400+ 1,000	400	400+ 1,000	400+ 1,000	400+ 1,000	400	400	400+ 1,000	1,000	400+ 1,000	400+ 1,000	400+ 1,000	400+ 1,000	1,000	400+ 1,000	400 + 1,000	400 + 1,000

Appendix 3

Radiocarbon dates and calibrated ages for ten samples from PFM004396. Individual calibration curves for the upper seven dates are also shown

Table of radiocarbon dates and calibrated ages.

Depth (cm)	Lab. ID	Sample ID	Weight (g)	^{14}C age	Interpretation/presumed reservoir age	Corr. ^{14}C age	Calibrated age ± 1σ (yrs BP)	Calibrated age ± 2σ (yrs BP)	Comment
44.5–45.5	Poz-10141	45A	9.1	2390±30	Litorina Sea/–400	1990±30	1990–1960 (18.2%)	2000–1870 (95.4%)	
							1955–1895 (50.0%)		
99.5–100.5	Poz-10183	100A	7.5	4150±40	Litorina Sea/–400	3750±40	4220–4200 (4.8%)	4240–3980 (95.4%)	
							4160–4080 (45.2%)		
							4040–3990 (18.2%)		
159.5–160.5	Poz-10184	160A	6.4	4270±35	Litorina Sea/–400	3870±35	4410–4370 (14.2%)	4420–4220 (84.9%)	
							4360–4230 (54.0%)	4210–4150 (10.5%)	
219.5–220.5	Poz-10185	220A	7.0	4505±35	Litorina Sea/–400	4105±35	4810–4760 (20.0%)	4820–4750 (23.3%)	
							4650–4250 (48.2%)	4730–4510 (69.3%)	
								4470–4440 (2.8%)	
279.5–280.5	Poz-10186	280A	7.8	5400±40	Litorina Sea/–400	5000±40	5860–5820 (11.6%)	5900–5780 (28.9%)	
							5750–5650 (56.6%)	5770–5640 (65.1%)	
								5630–5610 (1.4%)	
339.5–340.5	Poz-10187	340A	8.2	5040±40	Litorina Sea/–400	4640±40	5460–5380 (56.1%)	5570–5550 (1.3%)	
							5330–5310 (12.1%)	5480–5290 (94.1%)	
409.5–410.5	Poz-10189	410A	6.8	6350±40	Litorina Sea/–400	5950±40	6860–6820 (8.2%)	6890–6660 (95.4%)	
							6810–6720 (53.3%)		
							6700–6680 (6.7%)		
469.5–470.5	Poz-10190	470A	8.1	18,370±140	Yoldia Sea/reworked				small, 0.41 mg C
519.5–520.5	Poz-10191	520A	8.0	26,380±350	Yoldia Sea/reworked				small, 0.35 mg C
579.5–580.5	Poz-10193	580A	9.5	22,000±400	Yoldia Sea/reworked				small, 0.22 mg C